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MEMORANDUM REPORT

STUDY OF AIRPORT SURFACE TRAFFIC MOVEMENT PROBLEMS

Prepared by:

Edward J. Dowe

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June 1966

NOV 1969

FEDERAL AVIATION AGENCY
Systems Research and Development Service
Systems Analysis Division
Operations Analysis Branch
Washington, D.C.

MEMORANDUM REPORT

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This report does not necessarily reflect the Federal Aviation Agency's policy in all respects and it does not, in itself, constitute a standard, specification, or regulation.

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ABSTRACT

A study was made of the problems associated with the movement of aircraft and ground vehicles on the surface of the airport between the runway complex and the terminal building area. A description of the control process in both the taxiway and terminal subsystems is provided. Identification of factors pertaining to airport surface traffic movements was made, and a plan for simulation of ground traffic is furnished to determine the quantitative effects on delay by each primary factor. Several problem areas are discussed and a bibliography is included.

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SECTION 1

OBJECTIVES

INTRODUCTION. The objective of this project is to isolate, identify, and define the problems associated with surface traffic movements at airports.

SCOPE. Both aircraft and ground vehicles are included in the analysis of problems associated with airport surface traffic movements. The operational boundaries are established to include taxiways, aprons, passenger gates, ground vehicle lanes, by-passes, runup areas, and intersections of taxiways with runways and taxiways. The analyses will include air carrier, general aviation, and military categories of aircraft.

Refer to Figure 1 for a schematic representing the physical relationship of this project to the air/ground interface. The block labeled "Airport Surface System" lists the airport surface components to be treated in this effort.

PROJECT ASSIGNMENT. Project No. 430-003-01R, "Definition of Airport Surface Traffic Movement Problems," was assigned to the Research Division for in-house effort as part of Subprogram No. 430-003, "Airport Configuration Criteria." The Environmental Development Division is Lead Division for the Subprogram. This paper documents the results of project efforts from its beginning to December 1965.

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3-1A

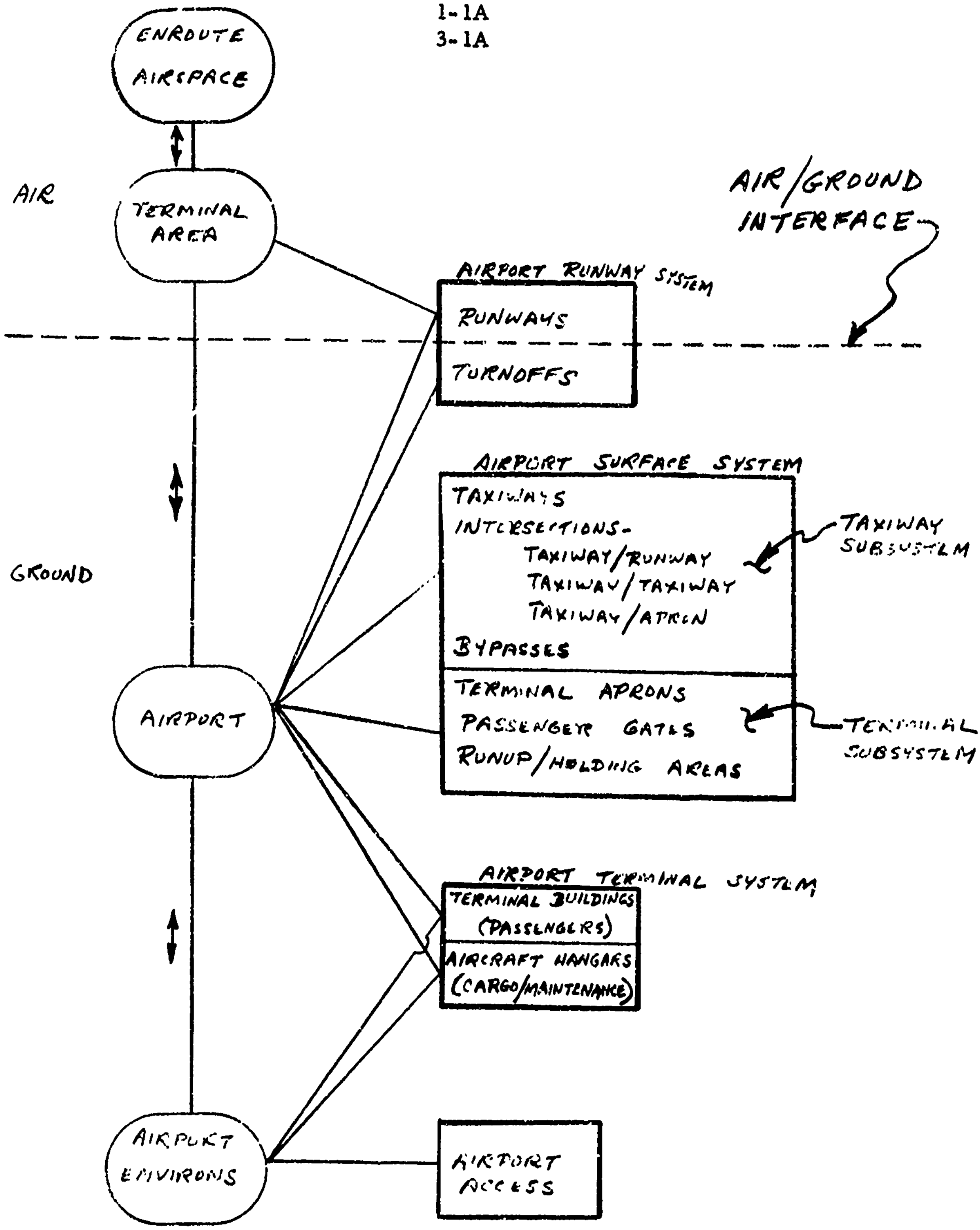


Figure 1. Airport System Schematic

SECTION 2

BACKGROUND. In carrying out its responsibility for safe, efficient use of airspace by both civil and military aircraft, the Federal Aviation Agency periodically examines and then predicts the national requirement for airports, and determines the character of the airport improvement program necessary to meet the needs of the aviation community. To assure that Federal and Private resources (both of which are limited and subject to competition with many other purposes) can be allocated effectively and efficiently to such a program, it is necessary to establish valid, meaningful principles for the design of safe, efficient, and economical airports.

To attain maximum usefulness in terms of practical application, such principles of airport design should be presented as quantitative rather than qualitative measures of performance.

A system approach is necessary because of the interactions between the airport and its systems, the terminal area, and more remotely, the enroute portion of the Air Traffic Control System (Reference F-1).

The Systems Research and Development Service has published a quantitative technique for measuring the practical capacity of an individual runway, or a runway complex, by relating movement rates to delays encountered by aircraft using the runways (References F-2 and F-3). With a knowledge of aircraft operating costs, it is then possible to evaluate an airport design (either for new construction or a proposed improvement) by assigning costs to the delays associated with specific movement rates. For a given movement rate, an efficient design will cause less delays, and cost less operationally, than a poor design. Therefore, individual designs can be compared and choices made between alternative proposals, balancing costs of construction (including land acquisition costs whenever applicable) against improvements to be attained.

The other related airport system that has yet to be analytically treated comprises the array of airport surface components exclusive of the runways. This will be referred to as the "Airport Surface System" (Refer to Figure 1) and included in the functional boundaries of this system are such components as:

Taxiways

Taxiway/taxiway intersections

Taxiway/runway intersections

Bypasses

Runup areas

Passenger gates and aprons

During busy or peak periods at some airports, limitations in the airport surface area can create bottlenecks to traffic flow, impose delays (which can be translated into additional operating costs), and in extreme cases restrict the airport's capacity. Every flight requires at least two ground movements - before take-off, a movement from the terminal to the runway start-to-roll position, and after landing, movement from the runway to the terminal. For example, departures can be delayed while taxiing out to the runway, and arrivals can be holding on the aprons waiting for gates. Such effects may persist for a considerable part of the busy interval, and recovery is often accomplished at the expense of adversely influencing operations on the runways.

Relief may be attempted by constructing or revising such facilities as taxiways or aprons. However, such construction efforts are very expensive and their extent may be limited by unavailability of land or similar restrictions.

Thus the airport surface system can become the critical or limiting factor to the expeditious flow of traffic under certain conditions. Examination and analysis of the factors that contribute to or influence the reaction of surface operations to an increasing traffic load could provide a basis for a better understanding of the system.

Summarizing, future airport planning requires consideration of the airport surface system. Annual increases in operations have been occurring at many major airports. Introduction of more sophisticated control techniques and equipments combined with the entry of higher performance aircraft into the system, will tend to focus attention on improving the efficiency of the airport surface. But physical changes in an airport usually involve substantial construction costs and take time. Thus accurate techniques are needed to analyze and compare the effectiveness of the components of the airport surface system.

SECTION 3

TAXIWAY SUBSYSTEM

Description of the Taxiway Subsystem Area

The taxiway subsystem area may be defined as that airport surface area, situated between the runways and the terminal apron, where departing and arriving aircraft are taxiing to and from the runways, constrained to operate within a network of paved taxiways, but including the crossing of active runways where necessary and use of segments of inactive runways to bypass a longer taxiway routing.

Thus it can be stated that the taxiway subsystem functions as the ground passageway between the runway system (where aircraft accelerate to and from flying speed) and the terminal system (where aircraft board and discharge passengers and cargo). See Figure 1. It is interesting to note that one study concludes that taxi time, as such, serves no useful end - being solely a necessary evil (Reference F-14). The conclusion is drawn that taxi time should be minimized and points out that unlike fixed wing aircraft, helicopters require no runways and consequently no taxiways between the runways and terminal.

1-1A
3-1A

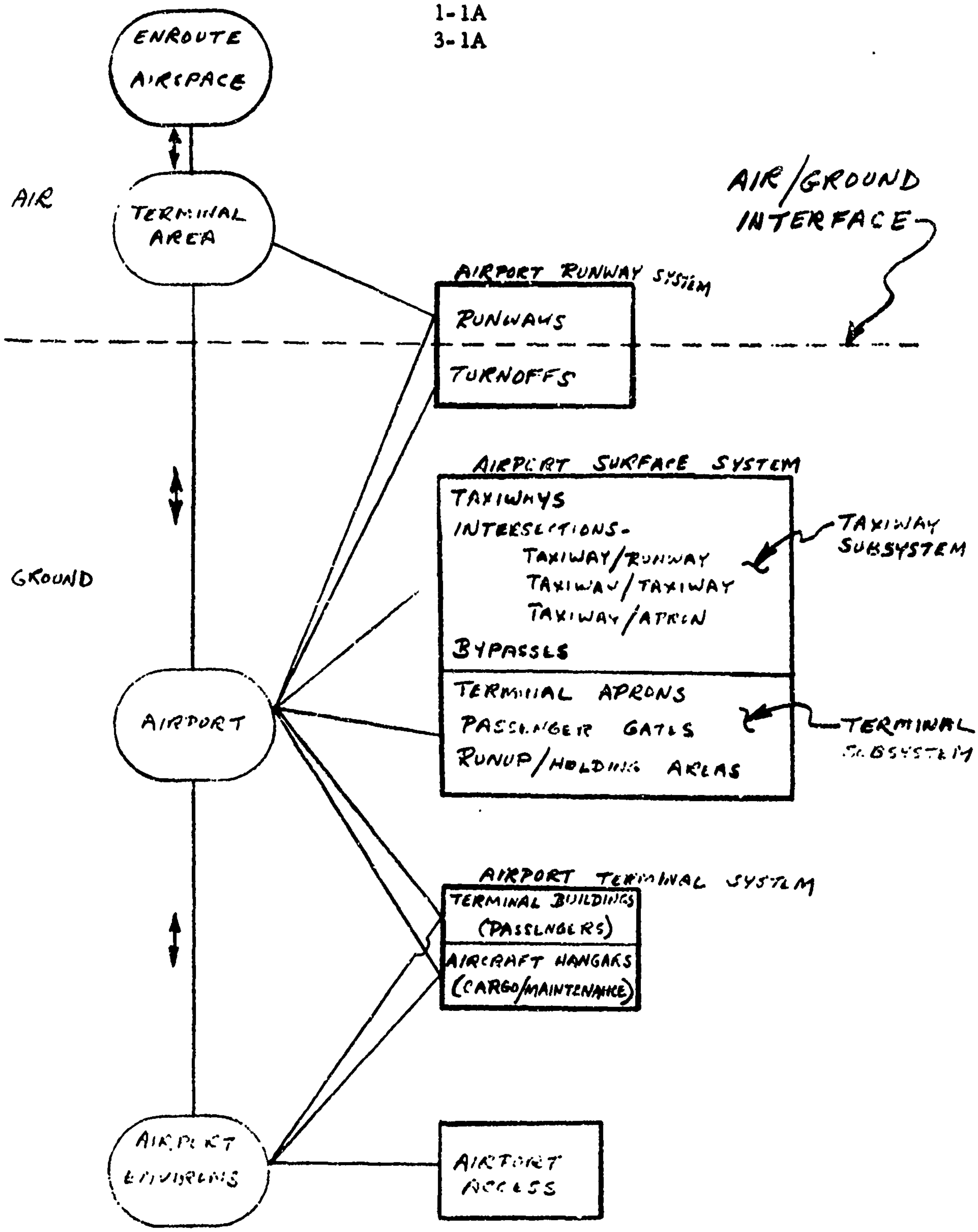


Figure 1. Airport System Schematic

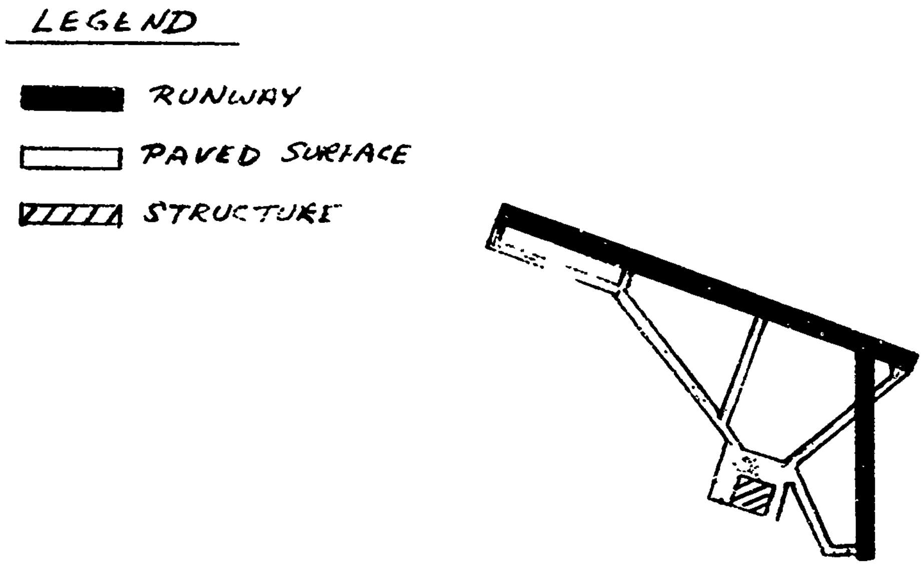


Figure 2. Example - Small Airport

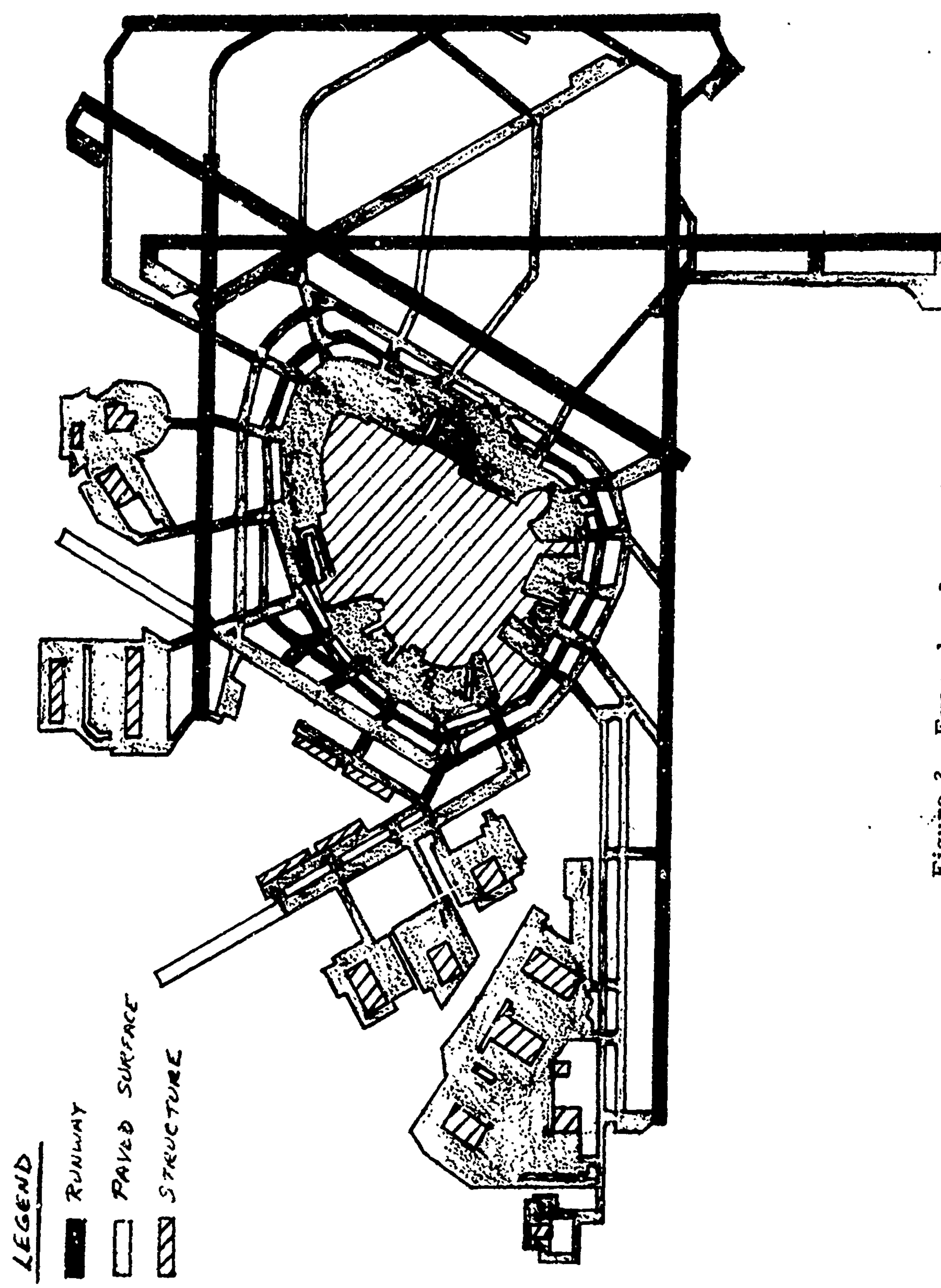


Figure 3. Example - Large Airport

General Considerations

Aircraft Limitations

The airplane is designed to perform efficiently in its primary environment - airspace. Of necessity, capability for ground travel must be provided but is limited lest airborne performance be degraded by weight, complexity, or maintenance penalties. Therefore, ground handling limitations such as restricted cockpit visibility and steering angle restraints manifest themselves during the ground taxi operation.

Characteristics of the Taxi Operation

The taxi operation requires that the pilot first, know which taxiway route he is to use, second, guide the aircraft safely along the taxiway, and third, avoid contact with other aircraft and ground vehicles. The larger airports have multiple runways situated in some instances at relatively great distances from the terminal, and the taxiway network provided to accommodate the runways and their turnoffs becomes a complicated layout of straight and curved taxiway segments that intersect each other and cross runways. See Figures 2 and 3 which illustrate the extremes of taxiway layout differences between a typical small single-runway general aviation airport and a large air carrier airport with intersecting runways and two sets of parallel runways. Some of the taxiway

complexity is unavoidable, reflecting the necessity to locate runways in less than optimum locations on the airport site because of restrictions imposed by land availability, construction costs, and topographical features or restraints due to noise abatement considerations.

At some of the large airports, it can take as long as 20 minutes to taxi from the terminal gate to the runway departure queue due to the distance involved as well as the number of intersections encountered en route. Taxiing is a maneuver that requires the pilot to anticipate future events if total taxi time is to be minimized (Reference F-7). The pilot must have adequate warning time, depending on his speed, to slow down or stop in order to avoid collisions with other aircraft or ground vehicles.

As an aircraft taxis toward an intersection, the pilot must know if there is a runway ahead where he may be required to stop and hold for traffic. If the intersection is with another taxiway, he must determine if another aircraft is approaching, and if he has to turn, the pilot must judge the angle of turn since a tight turn requires a slower speed than a shallow one. The required steering and turning maneuvers are functions of the size of the aircraft, width of the taxiway, and design of the taxiway network.

These are the restraints facing the pilot as he attempts to taxi to his runway or terminal at a reasonable speed (Reference F-7).

During conditions of reduced visibility, pilots exercise more caution and tend to slow down. If fog reduces the average taxi speed by one-half, then the total taxi time will double. For a more detailed discussion of taxi speed, refer to its coverage in a subsequent section.

Several pertinent factors emerge from consideration of the operational process of taxiing. They are:

(a) Control - the ground controller selects and advises the pilot of the taxiway route to be used to cross the airport. The ground controller also controls the crossing of taxiing aircraft over active runways. This aspect is examined subsequently in greater detail.

(b) Conflict Avoidance - the pilot is responsible for maintaining a safe longitudinal separation from aircraft or ground vehicles proceeding ahead of him on taxiways.

In the boundary area where the outer perimeter of the terminal apron joins the taxiway subsystem network, there are no formal control rules defining right-of-way, and each aircraft pilot operates within a type of VFR mode under a first-come-first-served basis for determining

priority of passage through the area if conflicts between two taxiing aircraft become imminent.

The ground controller is responsible for exercising control of two aircraft approaching a taxiway/taxiway intersection, but as is subsequently described, formal intervention and direction by the controller is seldom exercised at every taxiway/taxiway intersection. In practice, the pilots tend to engage in a self-regulating process at taxiway/taxiway intersections; for example, as two aircraft approach each other at such an intersection, the departure aircraft will usually maintain his taxiing velocity while the arrival aircraft will tend to slow down slightly, well in advance of the intersection, thereby allowing the departure aircraft to proceed through and be gone by the time the arrival aircraft is at the intersection. In observing taxiing operations during busy periods, it becomes apparent that the departure and arrival streams of traffic flow are normally segregated by the ground controller into separate flow patterns. More circuitous taxiway routings may be used instead of direct routings. This minimizes the mixing of arrivals and departures at taxiway/taxiway intersections.

(c) Guidance - the pilot is expected to keep the wheels of his aircraft within the bounds of the paved taxiway surface at all times. There is little difficulty in straight taxiways but becomes more complicated with large aircraft making sharp turns. This requires skill and judgment by the pilot who applies nosewheel steering to pivot his aircraft. In large aircraft he is situated ahead of the nosewheels and cannot see the main gear wheels. During the actual turning maneuver he must maintain aircraft speed high enough to overcome turning friction but low enough to avoid tire scrubbing while keeping the nosewheels on the paved surface (Reference F-7).

Also, he needs to know the identity of the taxiway he is occupying and where he is located in relation to the route he is taking. Various visual cues such as signs or identification devices, painted markings, lights, and airport maps are provided to help the pilot.

The Control Process

The control of aircraft taxiing about the surface of an airport is conducted on a cooperative basis between the controller and the pilot. It is useful to examine the ground control process in detail and attempt to gain an understanding of its operation in the taxiway subsystem.

Departures

The tower (ground controller position) does not know in advance what aircraft will leave which gates, but his experience with local traffic and familiarity with air carrier schedules allows him to antiicpate departure activity. When ready to leave the gate, the pilot of an aircraft will contact the tower requesting taxi clearance to the departure runway.

The tower then advises the pilot of the following

(a) The departure runway in use.

(b) The taxi route. The ~~tower~~ gc selects and assigns a taxi route from the gate to the departure queue. Routing is specific as to indivial taxiway identification between the apron and departure runway (i.e., the taxiway subsystem).

(c) Restrictions or precautions to taxiing, if any. Includes instructions to hold short of any active runways because all runway crossings by taxiing aircraft are controlled by the ground controller. The pilot is advised of any unusual conditions such as obstructions or pavement defects that may be encountered during taxi and the presence of any ground vehicles anticipated to be in the vicinity of the taxiing aircraft.

It is the responsibility of airport management, not the Agency, to issue regulations governing the operation of ground vehicles (for example, speed limits, right-of-way to aircraft, and transceiver capability). Airport regulations generally restrict ground vehicles from entry into the

taxiway subsystem area unless the vehicle is equipped to communicate with the ~~tower~~ gc, or is accompanied by another vehicle with such capability, or unless prior specific arrangements have been made with the ~~tower~~ gc for use of light signals in lieu of radio.

Since the ground controller is responsible for control of aircraft at taxiway intersections, he usually separates the arrival and departure streams of traffic flow in the taxiway subsystem.

As the taxiing aircraft nears the departure runway queue that may be forming, the ground controller transfers control of the taxiing aircraft to the tower controller. (At some prior time during the taxi process, an IFR clearance, if appropriate, has been delivered to the pilot by the ground controller or his assistant, and acknowledged by the pilot, but this action is not relevant to this study.)

Interesting examples of priority assignment of taxiing aircraft nearing the departure runway queue is illustrated in Figures 4 and 5.

Consider two departure aircraft approaching intersection A (Figure 4). There is no departure queue. The ground controller normally would assign an intersection priority to the aircraft making the earlier call from the terminal gate, and advise both aircraft to contact the tower controller when ready for take-off.

Transfer requires the changing of frequencies, a call-up by the pilot, and an acknowledgement by the pilot that he is ready-to-go, having completed his engine run-up or pre-departure checklist. This takes time, and in order to take advantage of __ arrival gap in landings, the tower controller may want to expedite the departure of the first available ready-to-go aircraft. Therefore, the ground controller would transfer aircraft 1 and 2 as soon as practicable.

Now consider Figure No. 5 where departures are delayed and the queue backs up to taxiways X and Y. This is not the usual situation and is indicative of long departure delays. Further, it is essentially a static condition, and priorities for movement from intersection A would generally be assigned by the tower controller by reference to the sequence of his flight strips which was established by the pilot calling in his ready-to-go status. But the sequence may have to be modified if the queue is blocked by an aircraft that is not ready. This illustrates the

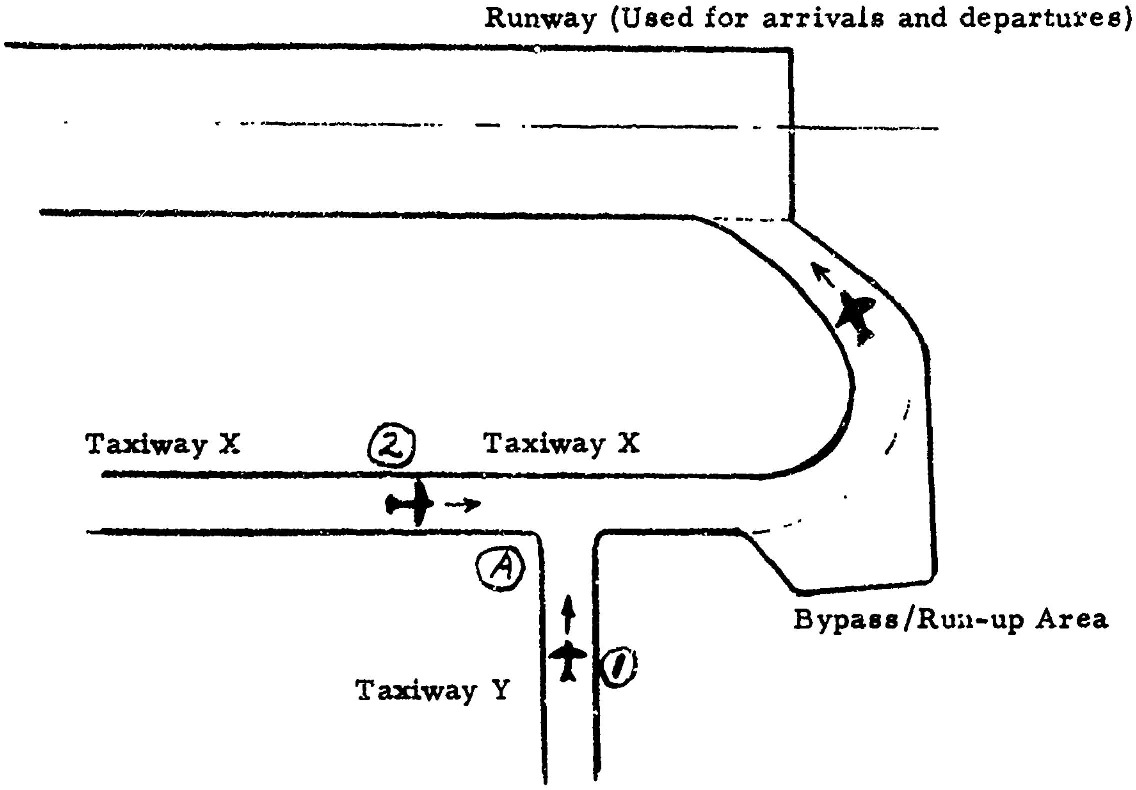


FIGURE 4. TWO DEPARTURE AIRCRAFT TAXIING TO LAST INTERSECTION BEFORE DEPARTURE RUNWAY QUEUE.

changing bases of sequence assignment, i.e., time of departure call-in from the gate, time of arrival at the last taxiway/ taxiway intersection, and time of ready-to-go call-in.

Arrivals

After the landing aircraft clears the runway, the tower controller transfers control of the aircraft to the ground controller. The pilot contacts the latter, requesting taxi clearance to his company gate (if air carrier) or the general aviation terminal (if corporate or private). The ground controller does not know in advance what aircraft will be arriving nor when, but he anticipates conditions because of his familiarity with air carrier schedules and local traffic conditions.

The ground controller then clears the pilot to his company gate area, without necessarily specifying a taxiway route. This differs from the departure taxi case because an arrival aircraft's destination is fixed while the destination of a departure aircraft is variable. More than one departure runway may be in use at the same time, and changes in prevailing wind direction may dictate the use of different runway combinations.

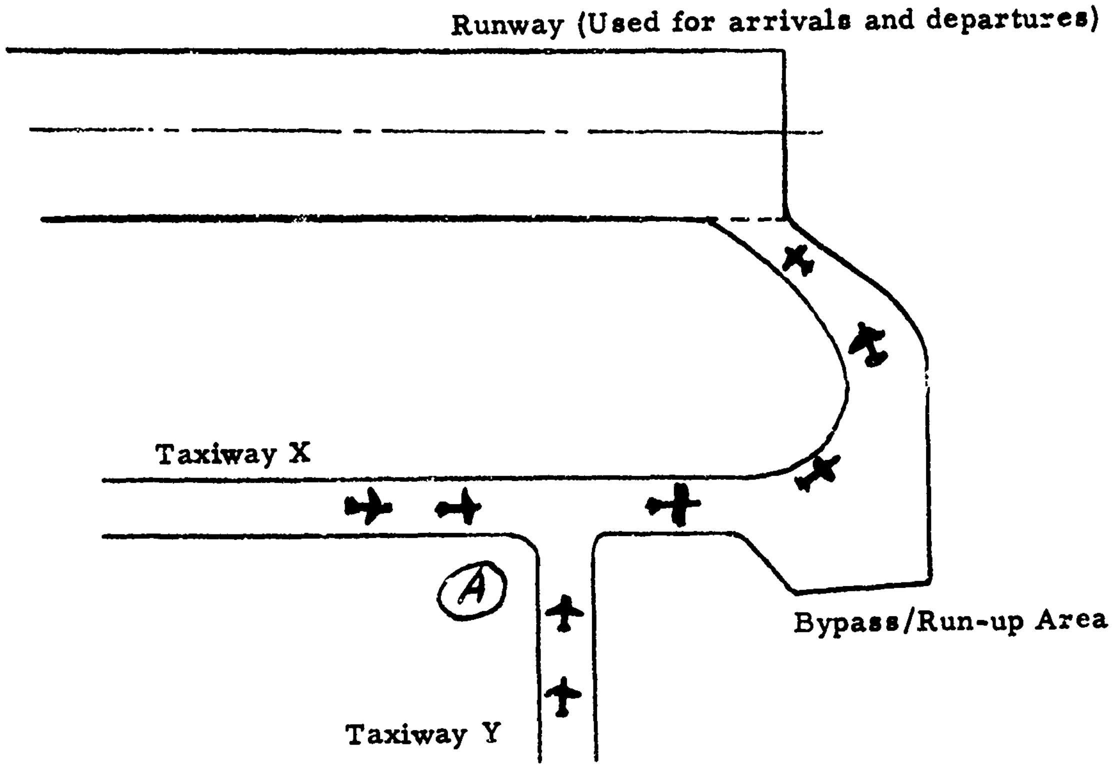


FIGURE 5. BACKUP OF DEPARTURE RUNWAY QUEUE EXTENDING TO TAXIWAY INTERSECTION.

The exceptions to this procedure are the crossing of active runways by arrival aircraft, or pilot unfamiliarity or confusion with the airport layout prompting his request for specific routing directions to the gate.

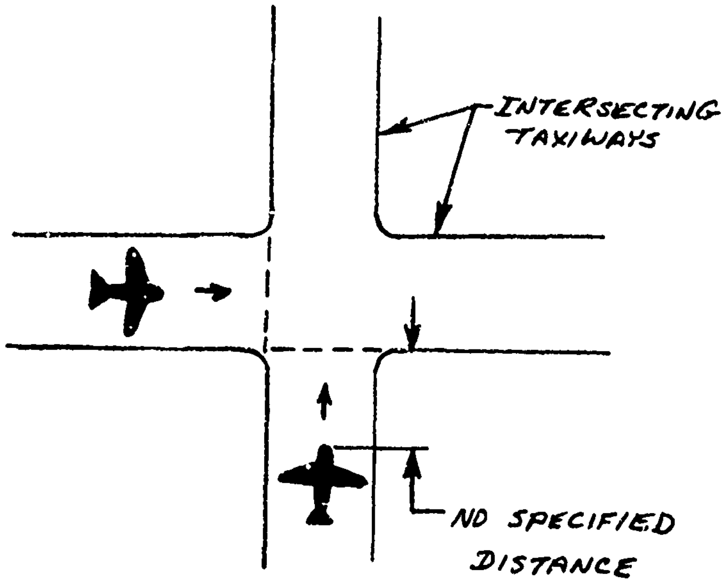
Assignment to a specific gate is the responsibility of the air carrier. At the larger air carrier airports, international flights generally receive this information on company frequency as long as an hour before landing while domestic air carrier flights may not know the gate assignment until they are nearing the company gate area.

The pilot does not contact ground control to advise that he has reached his terminal gate position.

Departures and Arrivals

Refer to Figures 6 through 8 for the three basic intersection situations that can be encountered in the taxiway subsystem. Figure 4 depicts the longitudinal spacing maintained between aircraft and/or ground vehicles.

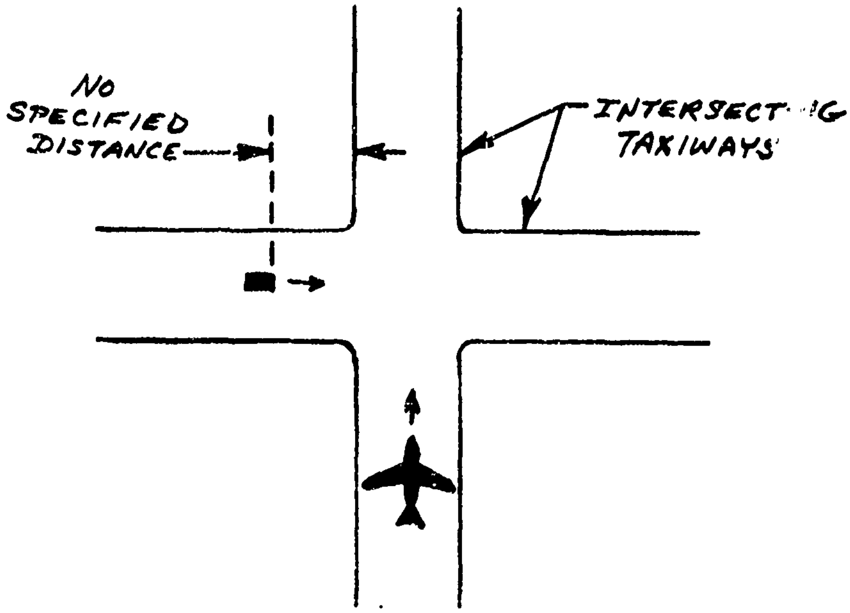
CASE I. TAXIWAY/TAXIWAY INTERSECTION - Aircraft/Aircraft



Priority Discipline	:	First-Come, First-Served
Control	:	If proceeding at the same rate towards the intersection, the ground controller is responsible for resolving the possible conflict situation. Refer to text for details.
Spacing	:	No specified distance from nose of waiting aircraft to edge of taxiway.

Figure 6. Taxiway/Taxiway Intersection - Aircraft/Aircraft.

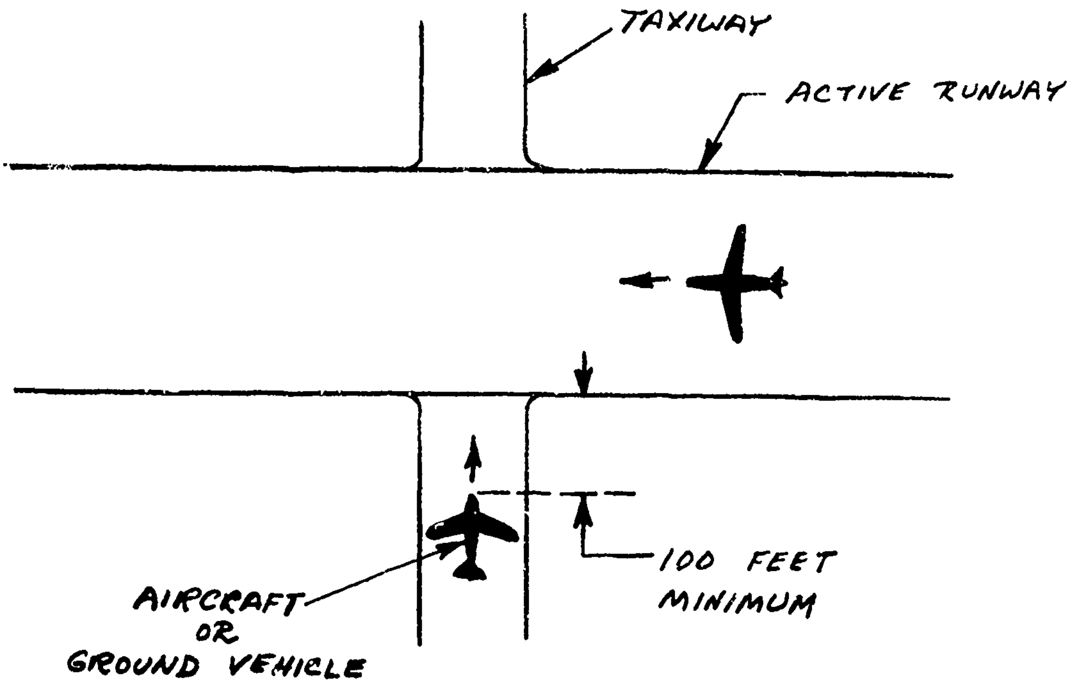
CASE II. TAXIWAY/TAXIWAY INTERSECTION - Aircraft/Ground Vehicle



Priority Discipline	:	Aircraft normally has right of way.
Control	:	Ground controller is responsible for prevention of conflicts.
Spacing	:	No specified distance from nose of waiting vehicle to edge of taxiway.

Figure 7. Taxiway/Taxiway Intersection - Aircraft/Ground Vehicle.

CASE III. TAXIWAY/ACTIVE RUNWAY INTERSECTION - Aircraft/Aircraft, or Aircraft/Vehicle



Priority Discipline	:	Runway occupant has the right of way. May or may not be in sight of taxiway occupant.
Control	:	The local controller maintains control of runway; the ground controller allows crossing of runway only after obtaining approval of local controller.
Spacing	:	Nose of waiting aircraft (or vehicle) must hold short at least 100 feet from runway edge.

Figure 8. Taxiway/Active Runway Intersection - Aircraft/Aircraft or Aircraft/Vehicle.

CASE IV. TAXIWAY SEGMENT - Aircraft Following Aircraft, Vehicle Following Vehicle, or Aircraft Following Vehicle or Vice Versa

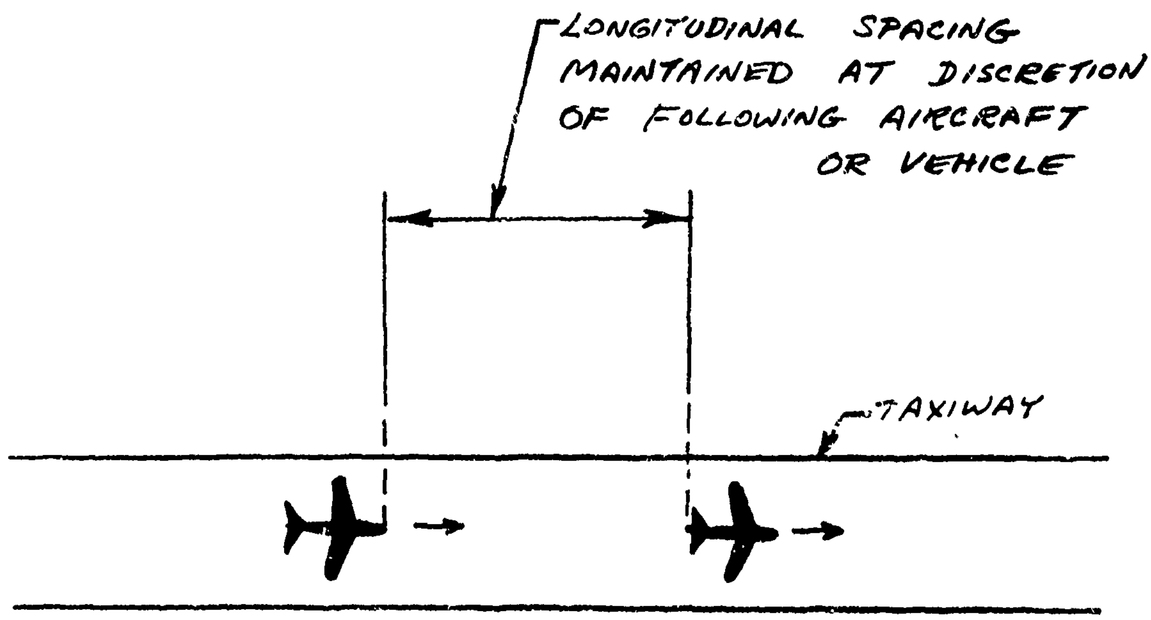


Figure 9. Taxiway Segment.

STRAIGHT DISTANCE (Feet)	AVERAGE SPEED (FPS)
0 to 1000	25
1000 to 1500	30
1500 to 2000	40
2000 t0 2500	50
Over 2500	60

TABLE 3-1. Average Taxi Speeds versus Straight Taxiway Distances.

Taxi Velocity

Field observations of taxi speeds at several airports (Reference F-13) disclosed that the major influence on taxi speed is the length of the taxiway section between intersections (see Table 3-1). For maximum taxi speeds for various aircraft classes, refer to Table 3-2.

AIRCRAFT CLASS	SPEED (FPS)
Heavy jets	60
Heavy pistor /turboprop, medium jets	60
Medium piston/turboprop, light jets	60
Light turn piston/turboprop	50
Single-engine light piston	40

TABLE 3-2. Maximum Taxi Speeds by Aircraft Population

SECTION 4

TERMINAL SUBSYSTEM

Description of the Terminal Subsystem Area

The terminal subsystem area may be defined as that airport surface area situated between the passenger gates and the outer periphery of the terminal apron where the taxiway network joins the apron.

General Considerations

Terminal Design

Rapid changes in design concepts for airport terminal buildings have occurred in recent years due to increases in volume of passengers, introduction of jet aircraft requiring larger ground turning radii than piston aircraft, and concern for walking distances required of the passengers.

As a consequence a wide variety of terminal configurations have been constructed (References C-3 and C-4) and many novel concepts have evolved.

The basic types of layouts for aircraft parking positions ("gates") can be categorized as follows: frontal, finger satellite, and remote. Boarding of passengers may be from the apron surface level or via elevated walkways or

mobile lounges at aircraft door level (Reference C-1). Aircraft parking procedures can be classified as being parallel, angle, or nose-in. Each of these variations in gates, passenger boarding, and aircraft parking will have certain advantages and disadvantages, depending on the type and volume of traffic and local preferences.

Since this study is concerned with surface traffic in the terminal subsystem area, only those terminal building factors that directly influence traffic flow are considered.

Aircraft Limitations

Limitations in nose gear steering and main landing gear pivoting action influence the time needed to maneuver an aircraft in or out of a gate position. The ratio of numbers of ground vehicles on the apron compared to the taxiways is of the order of ten to one, or higher, so any limitations in cockpit visibility would cause the pilot to be cautious during movement on the apron to avoid conflicts with ground vehicles, especially the smaller ones such as baggage tugs.

Characteristics of the Taxi Operation

Apron Taxi Distances

The locations of gates for air carriers and general aviation are fixed, particularly in satellite terminal

designs. On the other hand, runway utilization is variable, depending upon the prevailing wind direction or other considerations such as noise reduction restrictions, and the distance required to taxi in the terminal subsystem area varies. At the large airports, this complicates the basis for selection of an optimum location for gate locations in the terminal complex for each air carrier, and requires that other factors be considered, such as the location of company maintenance facilities at the airport, or convenient access to airport parking facilities.

Because of the number of ground vehicles operating within the apron area and mixing with taxiing aircraft, various schemes are used to channelize moving ground vehicles. For example, marked unidirectional lanes can be established just inside the periphery of the terminal apron.

The Control Process

As previously explained in the description of the taxiway subsystem control process, departure aircraft contact the ground controller to request taxi clearance to the runway in use. Upon receipt, the pilot will maneuver his aircraft away from its parked position (normally a company ramp man on the ground will help the pilot by hand signals to assure that this initial maneuver is executed without

undue difficulty). From his position on the ground, the ramp man can observe wing tip clearances more easily than the pilot. As long as the aircraft is within the bounds of the apron area, the pilot is solely responsible for conflict avoidance with other aircraft and ground vehicles. The operation is see-and-be-seen, aircraft having priority over ground vehicles, and no control is exercised by the ground controller. The same situation exists when arrival aircraft enter the apron area.

Historically, the apron area has never been subjected to ~~tower~~ atc control because of the impracticality of controlling a high density mix of diverse ground vehicles and taxiing aircraft in an area not fully visible to the tower cab. A large size aircraft effectively obscures the view of what is happening behind it.

Therefore, from a ~~tower~~ atc control standpoint, there is no requirement that ground vehicles operating in the apron area have communications capability.

In fact, an aircraft proceeding from a gate position to a maintenance hangar, for example, by a route wholly within the apron area, does not contact the tower for departure clearance. In general, rules such as speed limits are established by the airport operator and the various air carriers provide company rules to guide their pilots and surface vehicle operators.

SECTION 5 - PERTINENT FACTORS

INTRODUCTION

The extensive collection of airport surface observed data (References A-1 through A-4) were examined in detail to establish what factors can be considered pertinent to airport surface operations.

This identification of factors is necessary before attempting to analyze what factors influence surface operations, or the extent or degree to which movements are affected by such factors. Therefore, the following procedure was devised to treat the analysis of pertinent factors in three phases - identification, selection, and determination of effect.

1. Identification of Factors - The first step is to identify the factors that appear to be relevant. It is recognized that it is quite possible that important parameters may be overlooked while insignificant ones are included, but subsequent analysis should uncover such omissions.

2. Selection of Factors - The next phase is to delineate the important as well as the incidental factors by analysis of the relative importance of all the factors previously listed. This categorizes the primary parameters for further study.

3. <u>Effect of Factors</u> - The last and most important task is to determine the quantitative contribution that each parameter provides to airport surface operations.

I. IDENTIFICATION OF FACTORS

The operations taking place on the airport surface may be characterized by associating them with a physical environment or an operational environment.

The physical environment includes those factors that can be identified and assigned numerical values after appropriate measurement or analysis. Factors such as taxiway length and width, or aircraft populations, for example, are of a determinant nature.

The operational environment includes factors that are difficult to isolate since they pertain to actions involving human judgement and behavior as exercised by the pilot, controller, or ground vehicle operator either individually or in combination. By observation or by experiment it may be possible to handle such factors by obtaining the data needed to develop a statistical description of pertinent values.

The order in which factors are listed has no significance.

A. PHYSICAL ENVIRONMENT

For convenience, determinant factors are assigned to one of nine categories:

Aircraft Characteristics

Ground Vehicle Characteristics

Types of Operation

Pavement Configuration

Facilities

Traffic Composition

Traffic Control Procedures

Traffic Control Facilities and Equipment

Weather

1. Aircraft Characteristics

(a) Velocity and acceleration/deceleration rates, during taxi, average and maximum values for both straight away and turning.

(b) Velocity and acceleration/deceleration rates, during tow, average and maximum values for both straight away and turning.

(c) Aircraft type, size, wing span, length, landing gear geometry including wheel base (between Nose Landing Gear and Main Landing Gear).

(d) Turning radii (for various taxi velocities).

(e) Turning radii (for terminal apron parking).

(f) Nose wheel steering angles and limits.

(g) Cockpit visibility and height above ground.

2. Ground Vehicle Characteristics

(a) Velocity and acceleration/deceleration rates, average and maximum values, straight away and turning.

(b) Vehicle type, size, dimensions, weight, profile; self-propelled or trailer.

(c) Communication and lighting equipment, cab design.

3. Types of Operation

(a) Arrival

(b) Departure

(c) Taxi/tow

4. Pavement Configuration

(a) Geometric description of taxiway network.

(1) Width, length, number of segments.

(2) Number of alternative routes to and from each runway/trunoff combination.

(3) Number of intersections, taxiway/runway.

(4) Number of intersections, taxiway/taxiway.

(5) Number of intersections, taxiway/apron.

(6) Fillet radii at intersections.

(b) Variation in taxiway routing with changes in runway use or directions of operation.

(c) Geometric description of terminal apron.

(1) Number, size, location of gate positions.

(2) Methods of operating aircraft in and out of position.

(3) Passenger loading technique; use of covered walkways, mobile lounge, conventional ramps.

(d) Geometric description of cargo apron

(e) Geometric description of parking, service, and hangar aprons.

(f) Geometric description of bypasses, runup areas, and exit turnoffs.

5. Airport Facilities

(a) Spatial relationship between terminal area and runway complex.

(b) Spatial relationship between terminal area and hangars, aircraft parking, servicing, and fueling facilities.

6. Traffic Composition

(a) Aircraft mixtures, densities, and types of aircraft (air carrier, general aviation, military).

(b) Flight distance (local, continental, intercontinental).

(c) Ratio of arrivals/departures.

(d) Percentage of taxi/tows.

(e) Ground vehicle mixtures, densities.

7. <u>Traffic Control Procedures</u>

(a) Jurisdiction of ground controller.

(b) Procedural right-of-way rules.

(1) Aircraft versus aircraft.

(2) Aircraft versus ground vehicle.

(3) Ground vehicle versus ground vehicle.

(4) Aircraft versus tow.

(5) Tow versus ground vehicle.

(c) Special lanes for ground vehicles.

(d) Ground vehicle restrictions.

(e) Operational rules of priority.

(1) Active runway versus taxiway intersections.

(2) Overflow conditions, departure backups.

(3) Taxiway one-way versus dual directions.

(4) Takeoff and landing rules, active runways.

(f) Runway use, single, parallel, multiple, intersecting, short parallel, open-vee.

(g) Controlled versus uncontrolled surface areas, tower obstructed-vision areas.

(h) Helicopter operations.

8. Traffic Control Facilities and Equipment

   (a) Use of ASDE.

   (b) Communication with all/selected ground vehicles.

   (c) Equipment/displays for tower "blind spots".

   (d) Proposed detection/control/monitor systems.

   (e) Visual aids, route markers, signs, lights, lane markings.

9. Weather

   (a) Wind variability, direction, magnitude.

   (b) VFR and IFR operations, ceiling and visibility.

   (c) Runway/taxiway/apron surface condition (wet, dry, snow, slush, ice), traction, and braking.

   (d) Visibility, night, day, fog conditions.

B. OPERATIONAL ENVIRONMENT

1. Pilot Judgement

   (a) Guidance and aircraft control during taxi operation between runway/terminal/runway.

   (b) Selection of acceleration/deceleration rates and velocities during taxi.

   (c) Separation distances between other aircraft and ground vehicles.

   (d) Degree of flight crew familiarity with airport surface layout, ground aids, and rules of operation; degree of complexity of such facilities.

(e) Influence of pilot workload, proficiency, and cockpit/windshield layout.

(f) Visual aids (taxiway lights, taxiway marking, billboards, taxi route marker signs, apron markings).

(g) Proposed systems (runway crossing detectors/light signals, ground traffic control signals, directional signals).

(h) Jet exhaust separation clearances.

2. Controller Judgement

(a) Selection/assignment of taxi routes between terminal and runway.

(b) Conflict prediction/prevention between aircraft/aircraft and aircraft/ground vehicles.

(c) Active runway aircraft versus taxiing aircraft (or ground vehicles under tower control). Coordination with arrivals, departures, and arrivals/departures.

(d) Influences of controller workload, proficiency.

(e) Role of support equipment, ASDE, displays, communications, TRACE or similar, present/proposed.

3. Driver Judgement (Ground Vehicle)

4. Aircraft Control/Response Characteristics

   Taxiing, Turning, Braking, Parking

C. DESCRIPTION OF OPERATIONS

In analyzing operations occurring on the airport surface area within the context of the physical and environmental factors just enumerated, it is useful to identify the general categories of traffic flow. Vehicles can be classified as aircraft and non-aircraft. Further, the operational boundaries of the airport surface system can now be defined in detail to provide dimensions for the airport surface area.

AIRCRAFT

Operations can be categorized as follows:

1. Arrivals.
2. Departures.
3. Taxi/Tows.

Arrivals enter the system from the runway turnoff and proceed over the taxiway complex to a final stop at a passenger gate on the terminal apron. Departures leave the terminal apron and move to a runway departure queue area to await takeoff clearance. Departures are considered to leave the system when they enter this departure queue.

All other aircraft moving about the airport are classified as taxi/tows. The taxi designation refers to aircraft proceeding under their own power; tows are aircraft pulled by a ground tug. The taxi/tows represent those movements that did not originate as an arrival or terminate as a departure, and are a smaller percentage of total movements than arrivals or departures.

For example, data taken at three New York area airports (Reference A-2) incidates that during busy and peak hours, taxi/tows represent an average of four to 12 percent of total aircraft movements at LaGuardia, and three to seven percent at Newark.

Although taxis and tows normally carry no passengers on their way to or from a maintenance hangar or cargo loading area, the degree to which taxi/tows influence the movements of arrivals and departures should be determined.

Refer to Table 5-1 for a sequential breakdown of aircraft movements through the taxiway and terminal subsystems.

The reasons for stops and slowdowns of taxiing aircraft include:

a) Priority to landing aircraft (holding short at active runway)

b) Other aircraft on ground

c) Vehicles

d) Gate access delay

e) Runway clearance delay

f) Departure clearance delay

g) Unfamiliarity with airport layout

TABLE 5-1. SEQUENTIAL BREAKDOWN OF TYPICAL AIRCRAFT MOVEMENTS - ARRIVAL, DEPARTURE, AND TAXI/TOW

ARRIVAL	DEPARTURE	TAXI/TOWS
Turnoff	Taxi clearance requested from Ground Control	Taxi clearance requested
Various stops and starts during taxi	Taxi clearance issued	Taxi clearance issued
Stop and start during wait for gate space	Depart gate position	Depart original location
Park at gate position	Various stops and starts during taxi	Various stops and starts during taxi
	Arrival at apron area	Stop at d[illegible]ation
	Takeoff clearance requested	
	Cleared to enter runway	
	Takeoff clearance issued	
	Enter runway	
	Takeoff roll started	

Table 5-1. Sequential Breakdown of Typical Aircraft Movements

NON-AIRCRAFT

It is difficult to assign appropriate functional or operational categories to the diverse mixture of ground vehicles that move about the airport surface.

Table 5-2 lists the vehicles that are present at large metropolitan airports.

Vehicle speeds, driver visibility, vehicle size and maneuverability, environmental protection for the driver, radio communication capability, vehicle conspicuity for day and night operation, and vehicle lighting standards are variable and largely depend upon the function of the vehicle. These factors influence the driver during operation of his vehicle about the airport. In turn, although a moving aircraft has the right of wav, pilot judgement can be aided by effective ground vehicle conspicuity especially during night operations.

TABLE 5-2. TYPICAL AIRPORT GROUND VEHICLES

Vehicle Type	Single Unit	Multiple Units (Includes one or more Trailers)	Self Powered	Moved by Tug	Terminal Aprons	Area of Operation Taxiways/Runways
Fuel Truck	X	X	X		X	X
Baggage Train[1]		X		X	X	
Cargo/Mail Train[1]		X		X	X	
Food Service Truck	X		X		X	
Tug	X		X		X	X
Energizers/Starting Units	X		X	X	X	
Sanitary Service Vehicles	X		X	X	X	
Maintenance Trucks	X		X		X	X
Workstand Trucks	X		X		X	
Air Conditioning Vehicles	X		X		X	
Passenger Ramps	X		X	X	X	
Mail Trucks	X		X		X	
Refuse Trucks	X		X			X
Sedans	X		X		X	X
Fire Protection/Security Vehicles	X		X		X	X
Crew Bus	X		X		X	
De-icing Trucks (Winter)	X		X			
Snow Removal Equipment (Winter)	X		X			

NOTES:

1. A "train" consists of a tug with one or more trailing carts.
2. During construction or repair activities at an airport, dump trucks and other large construction equipments may traverse taxiways, aprons, or runways.
3. At Dulles International Airport, Mobile Lounges carry passengers between the terminal and aircraft parking area.

Reference C-1 suggests that approximately seven ground vehicles may be involved in servicing each aircraft. The exact number and mixture depends on such considerations as:

1. Flight status - A through flight aircraft requires less servicing than a turnaround.
2. Aircraft size and type - A large jet transport on an overseas flight requires more ground servicing support than a small two-engine local service transport.
3. Time of day - During busy or peak activity hours, aircraft turn around times tend to be compressed when arrivals are late and attempts are made to dispatch the airplane on schedule.

Thus, it can be seen that if twenty aircraft are on the terminal apron, approximately 140 ground vehicles can be expected to enter and leave the apron area. Ground vehicles outnumber aircraft in the apron area, whereas the situation is reversed on the taxiways.

Reference F-7 notes that the ground vehicular traffic is concentrated around the terminal, especially near the aircraft gates. During one five-minute period at JFK in 1964 (classified as an average peak hour operational period), 137 vehicle movements were counted. If this is projected to an hourly interval, it represents 1,694 vehicle movements. Such vehicles will not always use the same taxiways as aircraft, but this is a problem in the gate area as well as when they cross active aircraft taxiways.

SECTION 6

MODEL DESCRIPTION

TAXIWAY SUBSYSTEM

Objective

The first objective in this phase of the project was to attempt to formulate a mathematical procedure or model which could be used to describe the effectiveness of any given taxiway subsystem.

Description

A mathematical model is merely an expression of the operation of a system in mathematical terms. Its validity depends upon careful selection of the important factors affecting the operation being described. If every factor is included in the model in an attempt to make it valid under a wide range of operating conditions, the complexity of the model is increased to the point where solutions are intractable.

For example, wide variation exists in the layouts of taxiway subsystems. No two airports are similar, and differences in runway and terminal designs are reflected in the taxiways associated with them. However, certain basic elements occur in every taxiway subsystem, and it is useful to describe each layout in terms of:

a. Number of taxiway segments.

b. Number of taxiway/taxiway intersections.

c. Number of taxiway/runway intersections.

To make (a) more meaningful, each segment would be categorized as either short, medium, or long. If a runway was not in use due to wind or construction restrictions, such an intersection would be designated as (b), not (c), since it functionally serves as a taxiway.

Considerable effort was devoted to the selection of an appropriate measure of effectiveness. A good one should be:

a. Measurable.

b. Sensitive to changes in the operation of the system.

c. Related to the specific study at hand.

A common basis for all taxi operations is time. Because there is a possibility for conflicts between

a. Two taxiing aircraft at an intersection,

b. A taxi aircraft and an arrival/departure aircraft occuping a runway, and

c. A taxi aircraft overtaking another taxi aircraft on a taxiway segment,

delays occur. They include stops and waits at intersections or within taxiway segments, as well as slowdowns enroute.

One approach is to devise a theoretical limit for the time necessary to traverse the taxiway system, inbound and outbound for an aircraft of any category - such as the five population classes previously established in Reference F-2. During busy hours, delays will occur, but the extent of delay provides a basis for comparison, and by varying one factor at a time, should furnish the means to determine the influence of such factor.

To provide a basis for considering the theoretical limit of taxi time, and the various primary factors influencing the total taxi time, it is useful to consider a definition of the actual taxi flow rate:

$$\text{Taxi Rate} = \frac{1}{\dfrac{1}{\text{Arrival Rate (or departure rate)}} + \dfrac{\text{Average Taxi Delay}}{60}}$$

where: Taxi Rate = number of aircraft taxiing per hour

Arrival Rate = number of aircraft entering the taxiway subsystem per hour

Average Taxi Delay = Total taxi time, delay in minutes, incurred by the arrival/departure aircraft in the hour, divided by the total number of operations.

In evaluating the effectiveness of an overall taxiway system, the actual arrival and departure taxi rates may be used as the basis for assessing the influence that a factor may exert on minimizing delays.

Before developing a model, it is necessary to make certain assumptions about the variables to be entered in the formulation:

1. Reference F-13 contains a recapitulation of observed taxi speeds:

a. For straight distances:

Distance (feet)	Speed (fps)	mph
0 to 1000	25	17
1000 to 1500	30	20 ½
1500 to 2000	40	27 ¼
2000 to 2500	50	34
$>$ 2500	60	41

b. Maximum taxi speeds, by aircraft population:

Aircraft Class	Speed (fps)	mph
A	60	41
B	60	41
C	60	41
D	50	34
E	40	27 ¼

Aircraft Type	Mean Time, seconds
DC-3	20.3
Convair 240	23.8
DC-6	23.5
DC-7	30.5
Electra	23.5
Viscount	24.4
Light Aircraft	22.6

NOTES: 1. Mean for 49 samples is 23.2 seconds.
2. Standard deviation is 4.899.

TABLE 6-1. RUNWAY CROSSING TIME OBSERVATIONS

Class	Description
A	Jet Aircraft
B	Large Piston and Turboprops
C	Medium Piston
D	Light Twin Engine
E	Single Engine

TABLE 6-2. AIRCRAFT POPULATION CATEGORIZATION

c. Observations of Runway Crossing Times are provided in Table 6-1.

d. Aircraft are categorized into five classes (Table 6-2). For a traffic sample, refer to the Agency Center Peak Day Traffic Descriptions for Fiscal Year 1965. Select a large metropolitan airport and extract landings and departures, categorizing each as to aircraft classes.

2. It is assumed that no changes occur in the airport environment (visibility, character of paved surfaces).

3. Departure aircraft are assumed to enter the taxiway subsystem in accordance with the Poisson approximation to the binomial distribution.

4. Arrival aircraft are assumed to enter the taxiway subsystem randomly, subject to a minimum time interval of 50 seconds for a single runway configuration.

5. Aircraft following each other on a taxiway segment maintain a minimum of 350 feet longitudinal separation.

6. Taxi tows are not included.

In order to facilitate the selection of factors contributing to delay in the taxiway subsystem, and their quantitative contribution to same, the following process i[illegible]vised to simulate the arrival and departure streams of traffic in a taxiway subsystem.

Given a parallel runway configuration with its associated combination of taxiway segments, and taxiway/taxiway/runway intersections. Subject to the assumptions stated above, the first step is to generate two separate streams of aircraft - one a departure taxi group entering the taxiway subsystem at the outer perimeter of the terminal apron, and the other entering via the turnoffs from the runway.

The objective is to move each aircraft through the taxiway subsystem, thereby simulating the actual airport surface movement operation. Total delay for each movement is computed and compared to the theoretical limit.

Appendix II contains data and layouts for the thirteen runway utilization combinations used during a one-year interval at a large metropolitan airport (Figures II-1 and II-2). The departure taxi routings for each combination is detailed in Table II-3. Thus the traffic generation simulation program carried out for the first runway configuration can be repeated for the other twelve combinations.

Variations of the taxiway layout or routing, aircraft populations, and population densities should provide insights into the contribution of each factor to delay.

A similar approach can be applied to the terminal subsystem.

SECTION 7

EXAMINATION OF PROBLEM AREAS

Study of the characteristics of airport surface traffic movements in the taxiway and terminal subsystems suggest that the following generalizations apply to efficient designs:

1. The time required for an aircraft to taxi between the terminal and runway should be minimized.
2. The ideal taxi route is one that does not cross active runways.
3. The number of intersections should be minimized to reduce the probability of conflicts.
4. The most efficient route is the most direct straight-line distance with a minimum of turns.

Because these criteria may tend to contradict each other during application in the design of airport layouts, it is desirable to have available the quantitative contributions that the primary factors exert on delay in the taxiway and terminal subsystems.

Additionally, such guidance would be useful in studying the following problem areas:

a) Crossing of takeoff runways by taxiing aircraft.

b) Crossing of landing runways by taxiing aircraft.

c) Taxiing during conditions of reduced visibility.

d) Aiding the pilot in the navigation phase of the taxiing process (refer to Section 3).

e) Reduction of the frequency of potential conflict occurrences between aircraft and ground vehicles in the terminal subsystem.

f) Alleviation of ground control frequency congestion during busy and peak hours. Message contents include instructions as to runway use, taxiway routing, hold short of active runways, and associated instructions.

g) Reduction in delay encountered during the taxiing process, within the constraints of safety, passenger confort, aircraft/vehicle limitations, and economic resources for airport construction.

A general definition of the taxiway subsystem problem can now be offered:

1. Traffic Control - The traffic control problem in the taxiway subsystem area is to direct, route, and control random departures, random arrivals, and any vehicles or aircraft on the ground to assure that:

a) The active runways are protected from aircraft/ vehicles that want to cross.

b) Conflicts at taxiway intersections are prevented.

c) Traffic flow is expeditiously maintained.

2. Airport Design - The airport design problem in the taxiway subsystem area is to achieve a balance between taxiway capacity to support all combinations of runway configuration and runway system capacity. If the taxiway subsystem is not to restrict runway capacity, its flow rate capability must be equal to or greater than that of the runway.

SECTION 8

CONCLUSIONS/RECOMMENDATIONS

1. It is recommended that efforts be continued to determine the quantitative effects of primary factors associated with the taxiway and terminal subsystems.

2. The basis for proceeding with a simulation model for determinant factors is described in this report. Those factors relating to the operational environment involve actions involving human judgment and behavior as exercised by the pilot, controller, or ground vehicle operator, and it is necessary to treat these by observation or experiment.

3. The study and analysis of problem areas described herein should be pursued to develop improvements that can be applied to airport design criteria.

4. It is suggested that the project title be revised to better describe its scope and objective. "Factors Influencing Airport Surface Traffic Movements" is offered as an alternative to "Definition of Airport Surface Traffic Movement Problems."

APPENDIX I - RELEVANT AIRPORT ANALYSES, STUDIES, AND REPORTS

As part of the project effort, published studies and analyses pertinent to the airport surface area were examined, and references were selected on the basis of relevance. They are categorized according to purpose or scope.

A. Area Analyses

1. "Chicago Area Traffic Flow and Delay Analysis," Volumes I, II, and a Three-Section Vol. III, FAA, by Cook Research Laboratories, September 15, 1959.

2. "Terminal Area and Airport Surface Traffic, New York, Winter 1957-1958," Airways Modernization Board, by Airborne Instruments Laboratory, Report No. 4851-1, November 1958.

3. "Oakland Area Air Traffic Flow and Delay Analysis," Volumes I, II, and III, FAA, by Convair/Pomona, Report No. TM 339-83, December 1959.

4. "Atlanta Area Air Traffic, Spring 1959," Volumes I, II, and III, FAA, by Franklin Institute Laboratories/Philco Corp., October 15, 1959.

5. "Selected Extended Analysis of New York Data (1958)," FAA, by Airborne Instruments Laboratory, Report No. 5791-11, July 1959.

6. "Operations Analysis of Air Traffic Delays in the New York and Washington Air Route Traffic Control Center Areas on August 1, 1958," FAA, by Franklin Institute Laboratories, Report No. F-A2169-5, 1958.

B. Aircraft Performance Characteristics

1. "Runway Characteristics and Performance of Jet Transports in Routine Operations," Vols. I and II, FAA, SRDS, by Airborne Instruments Laboratory, March 1960.

2. "Runway Characteristics and Performance of Selected Propeller-Driven Aircraft in Routine Operations," Vol. III, FAA, SRDS, by Airborne Instruments Laboratory, April 1960.

C. Aprons/Passenger Gates

1. "Study of Mobile Lounge and Other Apron Traffic Delays at Washington Dulles International Airport," FAA, by Airborne Instruments Laboratory, W. J. Offutt, January 1961.

2. "The Need for More Gates and How to Get Them," Port of New York Authority, T.M. Sullivan, ASCE Miami Meeting, May 11, 1961.

3. "Airport Terminal Plan Study," FAA, by Airborne Instruments Laboratroy, P.H. Stafford, February 1962.

4. "Jet Airports - Passenger Terminal Building Design Principles," Architectural Record, Vol. 127, March 1960.

5. "Apron Control and Communications," by A.M. Lee, British European Airways Corp., "Shell Aviation News," January 1961, No. 271.

6. "Apron Requirements for Turbine-Powered Aircraft," IATA Annual Conference, Montreal, January 1958.

D. Taxiways

1. "On the Problem of Locating High-Speed Exit Taxiways," Paper by Dr. R.R. Read, ITTE' University of California, March 15, 1960.

2. "Exit Taxiways - Where and How Many," Paper by Prof. Robert Horonjeff, ITTE, University of California, May 1961.

3. "A Mathematical Model for Locating Exit Taxiways," FAA, by Institute of Transportation and Traffic Engineering, University of California, December 1959.

4. "Exit Taxiway Locations," Horonjeff, Read, and Ahlborn, FAA, by University of California, September 1960.

5. "Some Observations on Visual Lighting Aids and Taxiway Configuration for Large Jet Aircraft," by G.R. Stroud, International Air Transport Association Fifteenth Annual Conference, Lucerne, April 1963, Paper No. WP-124.

E. Ground Control Systems

1. "TRACE - Phase II," Proposal to FAA by Airborne Instruments Laboratory, April 1960.

2. "An Evaluation of the Traffic Capacity of a Fixed-Block Traffic Control System in the Approach Zone," by W.R. Rambo and R.C. Wheeler, Jr., Airborne Instruments Laboratory, Report ATA-2, July 15, 1947.

3. "Detection and Control of Aircraft on the Airport Surface," M.A. Warskow and J.E. Woodward, AIEE District Conference, Milwaukee, April 27, 1960.

4. "Doppler and Loop Tested for Runway Control," Barry Miller, Aviation Week, April 4, 1960.

5. "Airport Surface Detection Equipment," by A. Robertson, Interavia, November 3, 1960.

6. "Test and Evaluation of Taxiing and Routing of Aircraft Coordination Equipment (TRACE)," FAA, SRDS, Report Nos. 44-1-2X and -3X, E. L. Reamer, June 1962.

7. "Airport Ground Traffic Control - Port of New York Authority Airports," Martin A. Warskow, PONYA, April 1949.

8. "TRACE," Curtis C. Bogart, Journal of Air Traffic Control, October 1961.

F. Airports/Air Traffic Control/Traffic Flow

1. "Report of the Task Force on Air Traffic Control - Project Beacon," Richard R. Hough et al., Federal Aviation Agency, October 1961.

2. "Airport Capacity," Martin A. Warskow et al., Federal Aviation Agency, SRDS, by Airborne Instruments Laboratory, June 1963.

3. "Operational Evaluation of Airport Runway Design and Capacity, A Study of Methods and Techniques," E.N. Hooten et al., Federal Aviation Agency, SRDS, by Airborne Instruments Laboratory, January 1963.

4. "London Airport Ground Traffic Movement," Ministry of Civil Aviation, London, Report No. MCAP 68, 1949.

5. "Some Realistic Mathematical Aspects of Air Traffic Control," TDEC, by Franklin Institute Laboratories, Edward L. Fritz, June 15, 1955.

6. "The External Acceptance Rate of An Airport - An Analysis," ANDB, L.R. Philpott, Technical Memo. No. 3, June 22, 1951.

7. "Analysis of Techniques for Aircraft Ground Guidance at Airports," FAA, SRDS, by Airborne Instruments Laboratory, February 1964; SRDS Report No. 65-34.

8. "The Landing Capacity of a Runway," Alfred Blumstein, Journal of Operations Research, November - December 1959.

9. "An Analytical Investigation of Airport Capacity," Thesis by Alfred Blumstein, Cornell Aeronautical Laboratory, Report No. TA-1358-G1, June 1960.

10. "Airport Runway Capacity and Delays," Operational Research Center, University of California, Robert M. Oliver, Report No. 25, August 28, 1962.

11. "Delays in Terminal Air Traffic Control," Robert M. Oliver, University of California, AIAA Journal of Aircraft Vol. I, No. 3, June 1963.

12. "Aircraft Delays in Terms of Movement Rates on a Dual-Purpose Runway," Paper by Prof. T. Rallis, Technical University of Denmark, Copenhagen, November 1962.

13. "Airport Runway and Taxiway Design," FAA, by Airborne Instruments Laboratory, M.A. Warskow et al., July 1960.

14. "Airport Runway, Taxiway, and Ramp Design," Proposal to FAA by Airborne Instruments Laboratory, May 1959.

15. "Use of ASDE Radar as a Tool in Airport Research Programs," M.A. Warskow, IRE National Convention Record, Vol. 7, 1959.

16. "A Queuing Analysis of Airport Landing Congestion," by Robert W. Choisser, Autonetics Division of North American Aviation, ORSA Western Section Meeting, Honolulu, September 18, 1964.

17. "An Analysis of Traffic Flow," by H. Greenberg, ORSA Journal, Vol. 7, No. 1, January - February 1959.

18. "Transient Congestion in a Model of Runway Utilisation," B. L. Marks and Stella Hughes, Royal Aircraft Establishment Technical Note Math. 96, June 1963.

19. "Airport Capacity," March 26, 1964, and "Determining Capacity," April 6, 1964, Unpublished Papers by the Working Group on Airport Policy and Planning, FAA, Washington, D.C.

20. "Air Carrier Delay Measurements," FAA, SRDS, Report No. RD-64-78, June 1964.

21. "Airport Design," FAA, Airports Service, 1961, with Supplement No. 1 dated 1962.

22. "Layout of the Central Zone, Paris Orly Airport," Jacques Vosseur, Interavia, April 1961.

23. "An Analysis of Traffic Flow," by Harold Greenberg, Port of New York Authority, Journal of ORSA, Vol. 7, No. 1, January - February 1959.

24. "Statistical Analysis of the Flow of Highway Traffic through a Signaled Intersection," Paper by L.T. Newman, Brown University, April 1954.

25. "The Capacity of a Highway," by V.F. Hess, Institute of Traffic Engineers, August 1950.

26. "A Mathematical Model of an Air Transportation System," by T. W. Anderson, K.J. Arrow, and J.E. Walsh, Rand Corporation, Report No. RM-224, August 26, 1949.

27. "A Continuous Model of Transportation," by M.J. Beckmann, Rand Corporation, Report No. P-290, September 25, 1952.

28. "Maximal Flow Through a Network," by L.R. Ford, Jr., and D. R. Fulkerson, Rand Corporation, Report No. P-605, November 19, 1954.

29. "Dynamic Network Flow," by L.R. Ford, Jr., and D.R. Fulkerson, Rand Corporation, Report No. P-967, October 24, 1956.

30. "Speed, Headway, and Volume Relationships on a Freeway," by T.W. Forbes, Institute of Traffic Engineers Proceedings, 1951.

31. "Major United States Airports," Aviation Week, A Multi-Part Report beginning June 17, 1963.

32. "Staff Study - Elapsed Time and Costs in Air Traffic Terminals, FY 1961," FAA, Air Traffic Service, Program Control Division, April 1962.

33. "Development and Application of Mathematical Models for Determining Airport Capacity," by M.A. Warskow, Airborne Instruments Laboratory, Paper for the University of California Institute of Transportation and Traffic Engineering, November 1962.

34. "Airport Runway Traffic Design and Delays," by H.P. Galliher, American Society of Civil Engineers, Transportation Engineering Conference, Detroit, October 1962.

35. "The Confusion in Airport Planning," by Donald Canty, Architectural Forum, Vol. 117, July 1962.

36. "Solution Methods for Waiting Line Problems," Operations Standards Division, The Port of New York Authority, 1958.

37. "Airport Capacity," FAA, Airports Service, System Planning Division, Attachment No. 2 to AS 5090.1 dated September 22, 1964.

38. "How to Find the Practical Capacity of Streets," Anon., "Public Works," April 1950.

39. "Constructing Maximal Dynamic Flows from Static Flows," by L.R. Ford, Jr., and D.R. Fulkerson, ORSA Journal, Vol. 6, May - June 1958.

40. "Air Traffic Control and the National Security," Part B, Section II - The Airport, Air Coordinating Committee, Operational Policy Group, Washington, D.C., December 1950.

41. "Design for Tomorrow - The Changing Face of the World's Airports," Aeronautics, Vol. 43, pages 22-34, April 1961.

42. "Observations of Traffic Flow," F.L. Sawyer, Ministry of Civil Aviation ORS/MCA Report No. 6, London.

43. "London Airport Ground Traffic," Flight, January 12, 1950.

44. "An Analytical Investigation of Air Traffic Operations in the Terminal Area,"Robert W. Simpson, M.I.T., August 1964.

45. "Airports Planning Handbook", Chapter 2, "Instructions for Preparation of the National Airport Plan," FAA, Airports Service, February 2, 1966.

G. Simulation Approaches

1. "Simulation as a Means for Analyzing Airport Capacities and Methods of Airport Surface Control," Samuel M. Berkowitz, Air Navigation Development Board, by Franklin Institute Laboratories, Report No. F-2164-4, August 15, 1950.

2. "Factors Affecting Airport Capacity and their Applicability to Simulation," Vol. IV of IV subtitled "Airport Surface Area," FAA, BRD, by Airborne Instruments Laboratory, Martin A. Warskow et al., June 1959.

3. "Summary of Joint F.I.L. - T.D.E.C. Simulation Activities in Air Traffic Control," A.N.D.B., by Franklin Institute Laboratories, Berkowitz and Fritz, August 1955.

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5. "Graphic Simulation," by Robert Grubmeyer, Franklin Institute Laboratories, Paper for the SRDS "ATC Simulation Program Conference," June 1965.

6. "A Preliminary Report on Airport Surface Traffic Simulation," Thomas H. Green, FAA, Research Division, November 1960.

7. "Airport Simulator," Proposal No. J-8279 by Airborne Instruments Laboratory to FAA, February 1960.

8. "Simulation of Traffic Conditions at an Uncontrolled T-Junction," J.M. Aitken, Traffic Engineering and Control, October 1963.

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1. "Bibliography of Source Material on Airport Design and Applicable Methods of Theoretical Analysis," FAA, by Airborne Instruments Laboratory, Supplement I to Report No. 7601-1, July 1960.

APPENDIX II

RUNWAY UTILIZATION COMBINATIONS

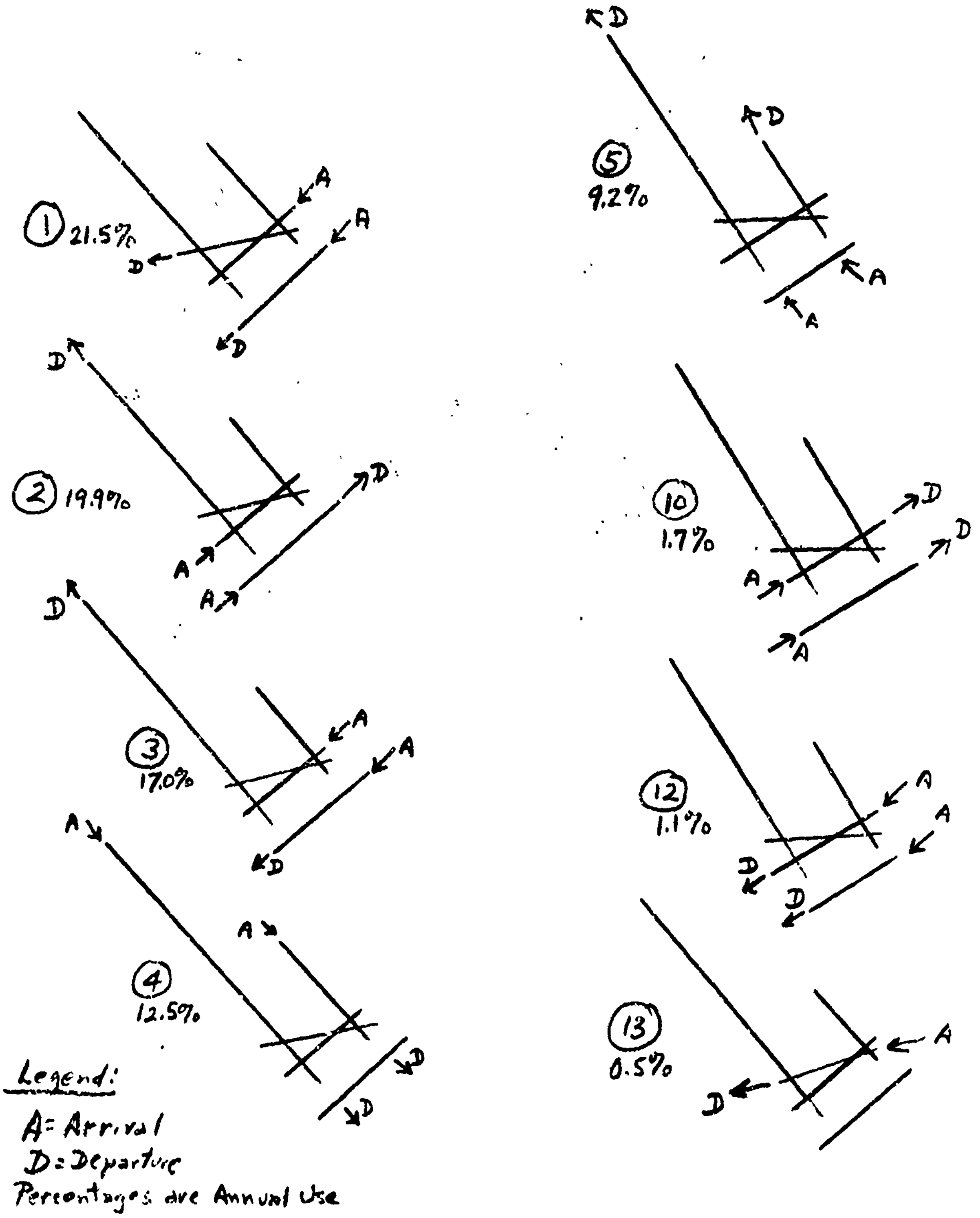
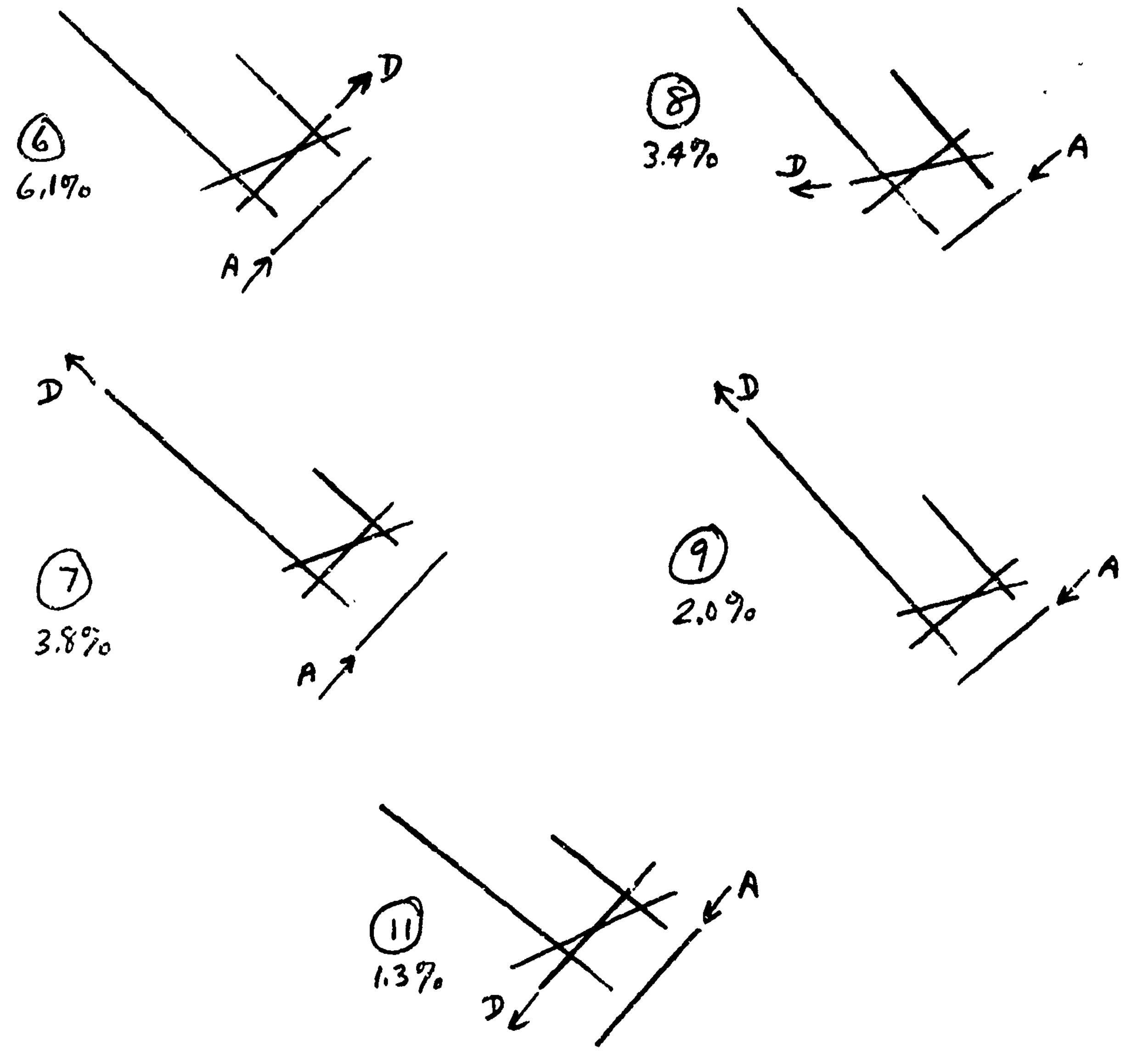


Figure II-1. VFR Runway Use Combinations



Legend
A = Arrival
D = Departure
Percentages are Annual Use

Figure II-2. IFR Runway Use Combinations

AIRPORT SURFACE DEPARTURE DATA

No.	1 Yrs. Sample-1963 % of Use	Runway Combination Take-Off	Runway Combination Land	Airport Surface Movement Routes: T = Taxiways R = Runways
1.	21.5%	25 22L	22R 22L 22R 22L	T-H, T-O, T-E, x31R, T-E, T-H, T-O, T-E, x31R, x25
2.	19.9%	4R 31L	4R 4L 4R 4L	T-H, xR 7, x4L, T-Z, T-TT, x31L, xK, T-J, T-O, T-K, x7, T-K
3.	17.0%	22L 31L	22R 22L 22L 22R	T-H, T-O, T-E, x31R, x25 T-H, x7, x4L, T-Z, T-TT
4.	12.5%	13L 13R	13R 13L 13L 13R	T-H, T-O, T-W T-J, T-O, T-P, T-DD
5.	9.2%	31R 31L	31R 31L 31R 31L	T-H, R-7, x4L T-J, T-O, T-K, x7
6. IFR	6.1%	4L	4R	T-J, T-O, T-K, x7
7. IFR	3.8%	31L	4R	T-J, T-O, T-K, x7
8. IFR	3.4%	25	22L	T-H, T-O, T-E, x31R, T-E
9. IFR	2.0%	31L	22L	T-J, T-O, T-K, x7, T-K
10.	1.7%	4L 4R	4L 4R 4L 4R	T-H, R7, T-K, 31L, T-H, x7, x4L, T-Z, T-TT, x31L, T-xK
11. IFR	1.3%	22R	22L	T-H, T-O, T-E, 13L, RU
12.	1.1%	22R 22L	22R 22L 22R 22L	T-H, T-O, T-E, 13L, RU T-H, T-O, T-E, x13L, x25
13.	.5%	25	25	T-H, T-O, T-E, x13L, T-E

83.4% - VFR
16.6% - IFR

Table II-3. Airport Surface Departure Data

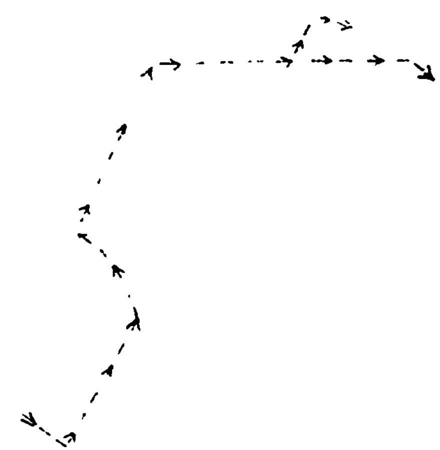
Notes
1. "x" denotes a [illegible]
2. Taxiways are de[illegible]
by alphabetical notation;
runways by num[illegible] notation.

Overlay No. 1

RUNWAY COMBINATION No. 1

21.5% Utilization (1963)

TAKE-OFF	LAND
(a) 25	22R, 22L
(b) 22L	22R, 22L



Departure Taxi Routes
from International Terminal.

When using (a) for take-off:

Aircraft crosses 1 runway, 3 taxi-ways, 3 vehicle lanes.

A/C uses for taxiing-3 taxi-ways, 1 runway.

Crosses the approach end of an active runway (22R)

No regress or bypass available

When using (b) for take-off:

Aircraft crosses 2 runways, 3 taxi-ways, 4 vehicle lanes.

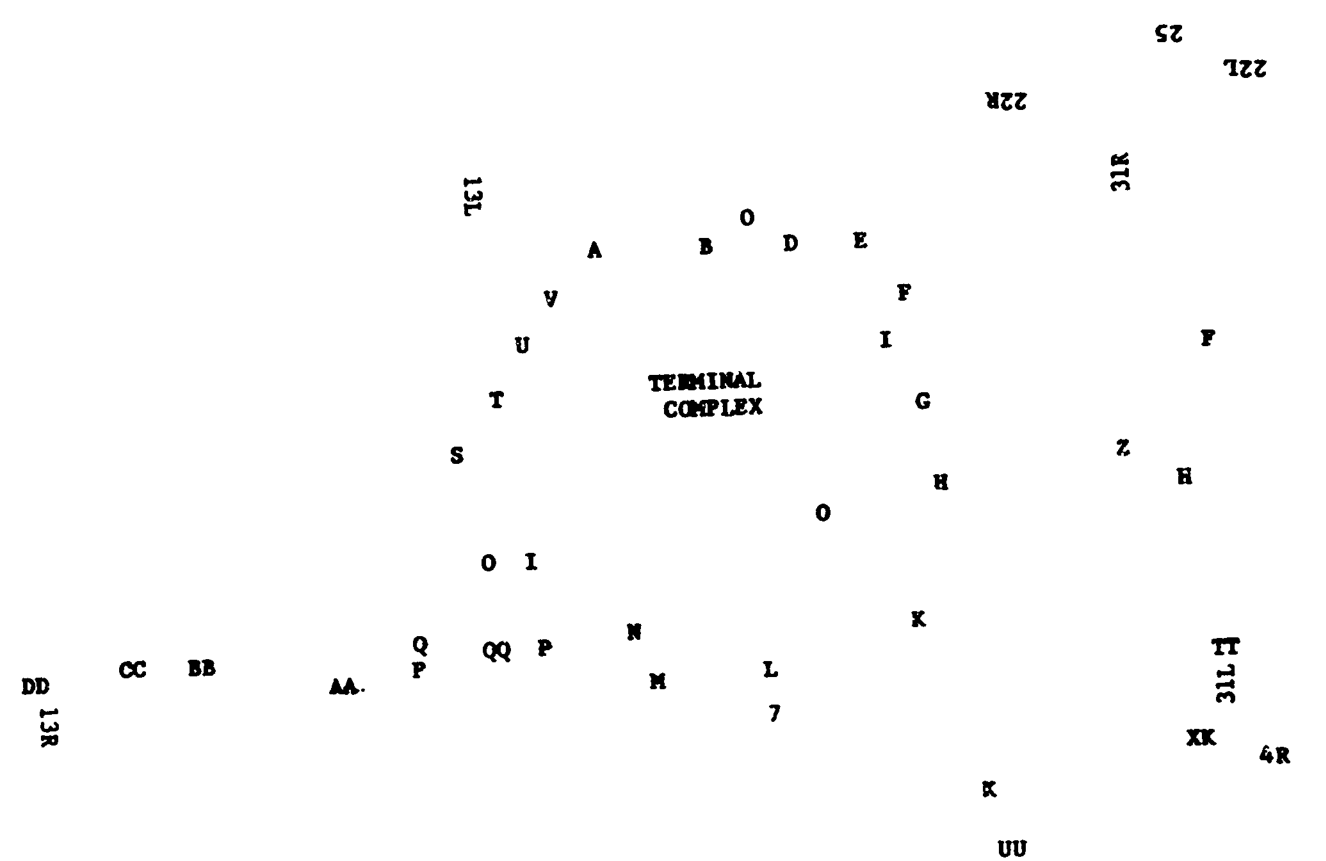
Uses for taxiing-3 taxiways, 2 runways.

Crosses the approach end of active 22R and active 25.

No regress or by-pass available.

Figure II-3. [illegible]port Surface Departure Data

Overlay No. 2



Fi... II-3. irport Surf... Departure Data

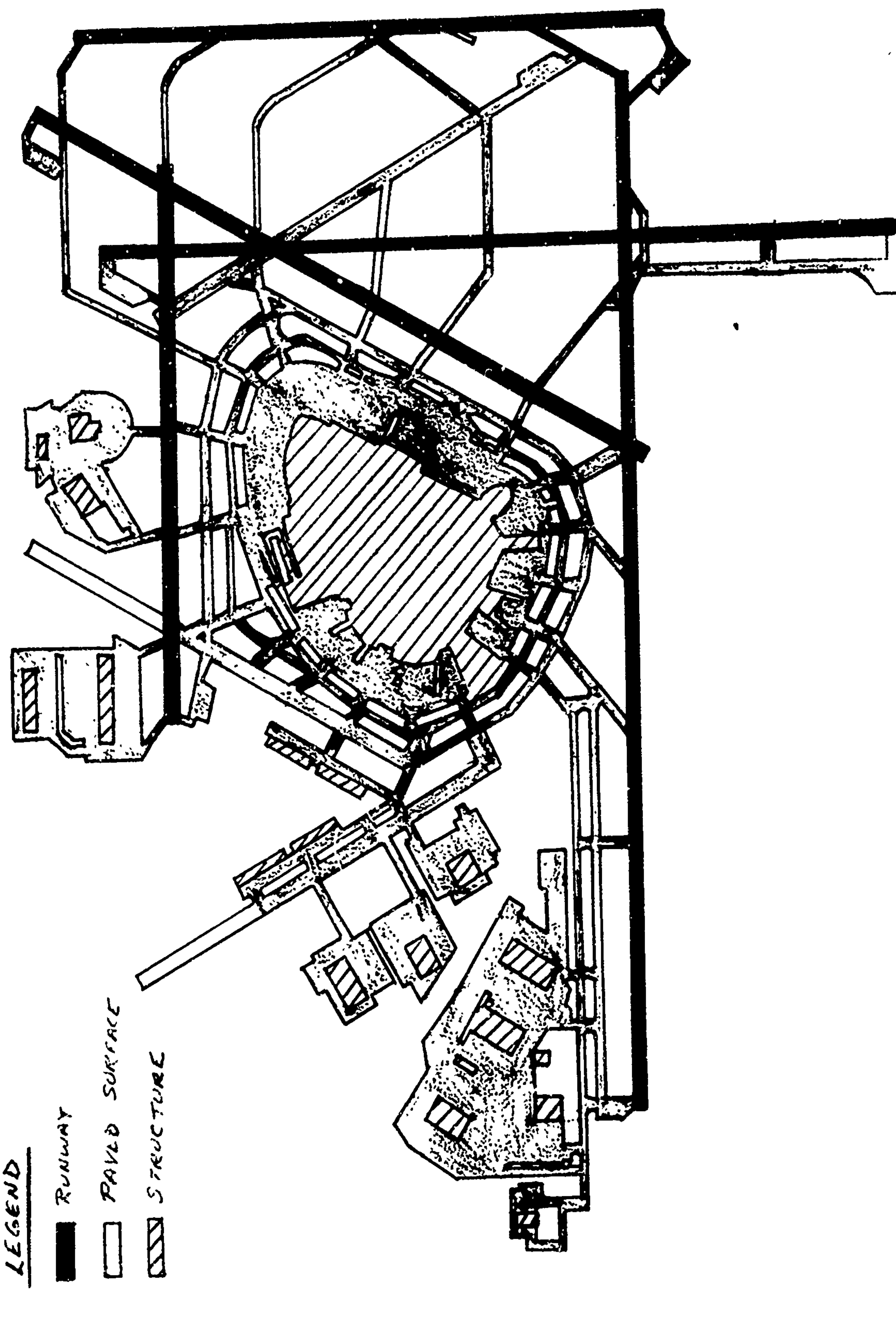


Figure 3. Example - Large Airport

ABSTRACT CARD

Federal Aviation Agency, Systems Analysis Division,

Washington, D. C.

STUDY OF AIRPORT SURFACE TRAFFIC MOVEMENT PROBLEMS by Edward J. Dowe, June 1966, xx pages, including illustrations (Project No. 430-003-01R).

Unclassified Report

Descriptors: Airport
Aircraft
Ground Vehicles
Airport Surface Traffic
Taxiway
Apron

A study was made of the problems associated with the movement of aircraft and ground vehicles on the surface of the airport between the runway complex and the terminal building area. A description of the control process in both the taxiway and terminal subsystems is provided. Identification of factors pertaining to airport surface traffic movements

was made, and a plan for simulation of ground traffic is furnished to determine the quantitative effects on delay by each primary factor. Several problem areas are discussed and a bibliography is included.